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Explosively Bonded Gun Tube Liner Development

William S de Rosset

prepared by

Oak Ridge Institute for Science and Education

Oak Ridge, TN 37830-0177

under contract ORISE 1120-1120-99

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14. ABSTRACT <p>The history of the Explosive Bonding Program is presented, starting at the initial Small Business Innovative Research Program in the late 1990s and continuing to the present. The program has been funded by different agencies throughout its history, with an emphasis on eliminating chromium coatings from gun tubes. The current state of the art is assessed through the use of Technology and Manufacturing Readiness Levels.</p>					
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1. Introduction

The path from a breakthrough in basic research to actually fielding a concept can be a long and tortuous one. This is especially true when the fielded component or system is large and expensive. One such example is the work done to put a temperature-resistant metal liner in the 25-mm M242 Bushmaster gun tube. Referred to as the Explosive Bonding Program (EBP), it was not a single effort but rather was conducted under a number of funded programs. This report documents the history of this effort, dividing it into various stages. The early research into explosively bonded metal liners is presented in Section 2. Following sections take the work to the present, citing dates and milestones. At each stage, a Technology Readiness Level (TRL) and Manufacturing Readiness Level (MRL) are assigned to see how far the development has progressed. The final section reviews the history and provides lessons learned about the conduct of research in US Army laboratories and research centers for this particular program.

2. Early Liner Development

There was a great deal of gun-tube liner research conducted after World War II to enable what were called hypervelocity guns.¹ These efforts identified several promising materials that could be used for liners, primarily refractory metals such as tantalum (Ta), molybdenum (Mo), and tungsten (W). One of the main technical hurdles was to securely attach the liner to the gun tube, which was successfully achieved by 2 processes: swaging² and co-extrusion.³ This work did not result in fielding any lined barrels.

Research by the National Defense Research Committee in the 1940s found that Stellite 21 used as a partial liner in the 0.50-cal. machine gun barrel was extremely effective in extending its service life.⁴ This liner was shrunk-fit into the barrel and mechanically held in place on either end by shoulders in the barrel. This liner has been used since 1945 in several different machine gun barrels.² The liner arrangement fails occasionally due to propellant gas getting between the liner and gun tube,⁵ and it is presumed that the bond strength between the liner and gun tube is not strong enough to resist the propellant pressure.

In 1998, a Small Business Innovative Research (SBIR) program was awarded to TPL, Inc. (Albuquerque, NM), the goal of which was to explosively clad a Ta liner to a large-caliber smoothbore gun tube. The metallic bond produced by explosive bonding is extremely strong and presumably would keep the liner in place. In Phase 1, TPL demonstrated the ability to bond Ta to gun-tube sections. Examination of the bond by Benét Laboratories (Picatinny Arsenal, NJ) showed

that the work was promising enough to proceed to Phase 2.⁶ However, it was quickly realized that the original goal of cladding a large-diameter barrel was much too expensive to be accomplished with the limited funding available. Consequently, the scope was reduced to cladding a half-length, 25-mm M242 barrel with pure Ta.⁷

TPL was provided with 3 used M242 barrels whose rifling was machined away by ARES, Inc. (Port Clinton, OH), after the barrels were truncated. TPL was able to explosively clad pure Ta to the truncated barrels. ARES also provided the final honing of the liner and machined straight grooves in one of the liners. (The M242 has a progressive twist to the rifling.)

Firing tests were carried out at Aberdeen Proving Ground, MD, with an experimental version of the M919 kinetic energy penetrator round. This round had an extremely high flame temperature and was chosen to accelerate the wear produced by the tests. Previous tests of this ammunition with a standard barrel were halted at 375 rounds due to melting of the gun tube. The Ta-lined barrel was fired 1,385 times. Firing stopped when the available ammunition was expended. The rifled tube was fired 600 times. Both tubes appeared to be operating satisfactorily at the end of the tests. Dispersion and muzzle velocity measurements were not taken during the tests. However, visual observation of the tracer paths indicated that the dispersion was reasonably good.

The gun tubes were sectioned and examined for damage.^{8,9} Figure 1 shows the sectioned smoothbore gun tube near the breach. Extensive damage to the liner can be observed. It is difficult to reconcile the amount of damage to the liner and gun tube with the observations of satisfactory gun tube performance.

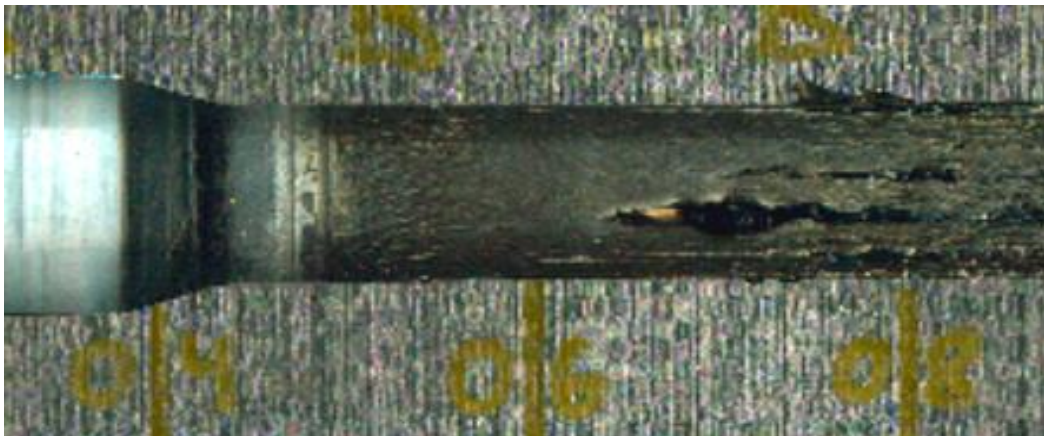


Fig. 1 Smoothbore M242 gun tube with a Ta liner. Extensive damage to the liner and gun tube can be seen near the breech.⁹

Figure 2 shows a cross section of the liner and gun-tube interface. What is remarkable about this micrograph is that the liner is adhering to the remaining steel even as the steel is being eroded away by the propellant gases. This is quite different from chromium (Cr) coatings, which flake off when cracks in the coating forms islands. Of some concern was the occasional appearance of iron-Ta intermetallics near the liner-steel interface. This is a brittle phase and subject to cracking. However, the presence of intermetallics did not seem to affect the adherence of the liner to the steel where no through-cracks were observed.

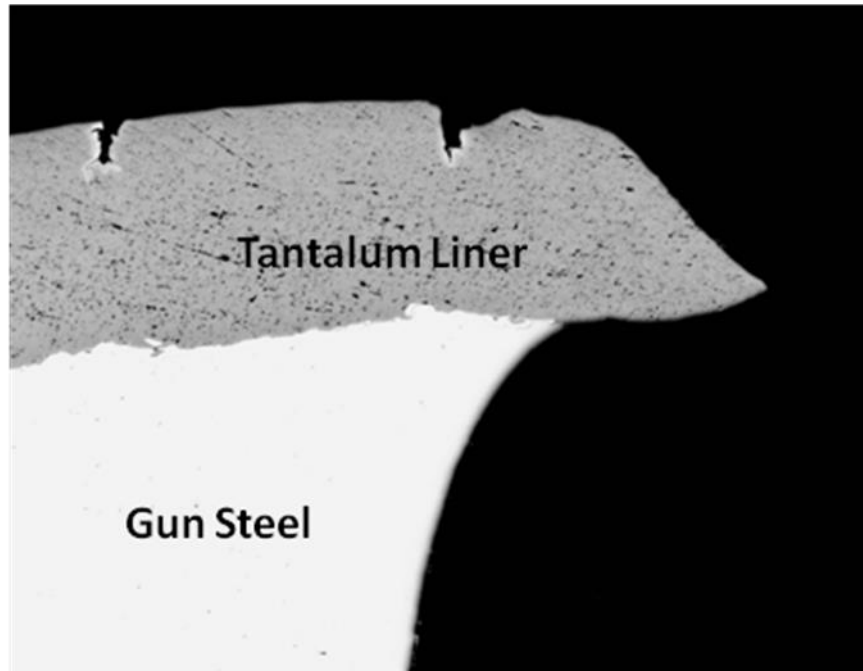


Fig. 2 Micrograph of cross section of liner and gun steel. The Ta liner strongly adheres to the steel substrate even as the steel is being eroded from beneath it.⁹

The tests were considered a success in that the number of shots fired through the lined gun tube was far in excess of the number fired through the Cr-coated gun tube. The test results also confirmed the hypothesis that explosive bonding would provide the bond strength needed to keep the liner in place during firing.

The purpose of the SBIR program is to encourage small businesses to bring a product to market. It was assumed that all that was needed at this point was to choose a suitable liner material, explosively bond it to an M242 tube, rifle the liner, and demonstrate the barrel by test-firing it. As it turned out, the path to fielding this technology was much more difficult than originally imagined.

There are several important parameters critical to produce an acceptable bond. The explosive bonding process used to bond liners to gun tubes is presented in Appendix A, which explains the important explosive bonding parameters. The

initial success of this effort obscured the fact that no fundamental research and development had been carried out in explosive bonding technology applied to gun-tube liners, at least at the relevant US Army research organizations. A case can be made that the technology was at a TRL of 4 since the truncated M242 with the Ta liner might be considered a breadboard. (See Appendix B for the definitions of TRLs.) It can also be argued that at this point the effort had not reached an MRL of 1, since most of the manufacturing issues had yet to be identified (see Appendix C for the definitions of MRLs).

3. Mantech Program, 2004–2005

In late 2003, Benét Laboratories contacted the US Army Research Laboratory (ARL) concerning a cooperative effort as part of the Manufacturing Technology (Mantech) Program (MTO #0403; Durable Gun Barrel, Explosive Bonding) they were pursuing. This effort was a part of a larger Mantech program conducted by the US Army Armament Research, Development and Engineering Center (ARDEC). Its goal was to provide the manufacturing technology necessary prior to fielding the explosively lined gun tube. A kick-off meeting was held in April 2004 at Benét Laboratories; ARL was assigned the task of liner material selection.

In retrospect, the jump into a Mantech program may have been premature. Explosive bonding had been used for decades prior to the gun-tube work but mostly joining dissimilar materials in a flat-plate configuration. Liner material research had been going on since World War II, so there were many materials to choose from. Even though the technology showed a great deal of promise, there was no funding available from mission or core programs to advance its development. The fact that the work began under an SBIR program may also have complicated matters with intellectual property rights issues. In any event, the technology was pursued in programs where funds were available.

Soon after the Mantech program began, ARL recommended 4 candidate liner materials: 1) Ta-10% W (Ta10W); 2) Ta-5% W-2% Mo; 3) Ta-4% Mo (Ta4Mo); and 4) Stellite 25. Later, Ta4Mo was replaced by Ta-5% W (Ta5W) and Ta-2.5% W (Ta2.5W) was added. Several factors were considered in the choice of these materials. Melting point was a prime consideration, so choices were made from refractory metals. Pure Ta was rejected because its strength was too low to resist forces on the lands in a rifled tube. However, it could be considered for smoothbore tubes like the M256 120-mm tank cannon. Cost was also a consideration. Past research showed that rhenium was an excellent liner material¹⁰ but it was too expensive. Material availability, ductility, strength, and machineability were also taken into consideration.¹¹

TPL was selected to carry out the explosive bonding. The goal was to bond one of the candidate liner materials to a full-length M242 gun tube. The process of explosively bonding a liner to a gun tube is described in Appendix A. Briefly, the liner is filled with explosive, placed inside the gun tube, and the explosive is detonated. This drives the liner against the gun tube wall and, in effect, welds the liner to the gun tube. Critical elements of the process are the characteristics of the explosive used, the liner dimensions, and the initial distance between the liner and gun tube wall (standoff). The purpose of the SBIR program that started the explosive bonding effort was for TPL to find a use for explosives recycled from old munitions. Thus TPL felt constrained to some extent in the choice of explosive.

The following suppliers were identified as sources of refractory metal tubes: Eagle Alloys (Talbott, TN), AT Wall (Warwick, RI), HC Starck (Newton, MA), and Deloro Stellite (Ontario, Canada). The wall thickness for the tubes was chosen somewhat arbitrarily at 0.075 inch (1.9 mm). Thermal effects calculations made by Witherell¹² much later indicated that 0.010 inch (0.25 mm) would be necessary for the liner thickness in the M242 to prevent a phase change of the underlying steel.

Explosive bonding experiments were begun at TPL at the end of the year. TPL used a 10-inch section of an M242 tube with stepped increments in its bore diameter. The purpose of the experiments was to determine the optimum standoff distance. Work continued into 2005, at which point TPL was only able to bond to the Ta2.5W liner.

It was decided to go forward with the Ta2.5W material. TPL was tasked with bonding liners of this material to 3-foot sections of M242 gun tubes. The thicker rear section of the gun tube was used for each trial so that momentum traps, needed for thin-walled tubes, could be avoided. Three truncated M242 gun tubes (~3 ft long) were provided by Benét Laboratories to TPL, who then coordinated the bore honing, rifling removal, Cr removal, and obtaining the correct geometry for cladding. TPL then explosively clad each of the tubes with a Ta-2.5W liner provided by 1 of 3 candidate companies: AT Wall, Eagle Alloys, or HC Starck. The clad tubes were then sectioned and samples were distributed by TPL to Benét Laboratories and ARL for analysis and characterization. Analysis included micro-hardness, metallurgical analysis, microscopy, and elemental analysis.

Mixed results were obtained from the examination of the rings. In all cases, when the rings were cut in a radial direction, the ring sprang open. Figure 3 shows ring 4 taken from near the breech of a tube with an Eagle Alloys liner, which illustrates this effect.¹³ It confirmed earlier findings from X-ray diffraction studies

that residual stress was present in the gun tube after explosive bonding. In some cases the liner separated from the gun tube, indicating a weak or nonexistent bond. Micrographs of the liner–gun tube interface showed either a flat interface or a wavy one, the latter generally a sign of a strong bond.

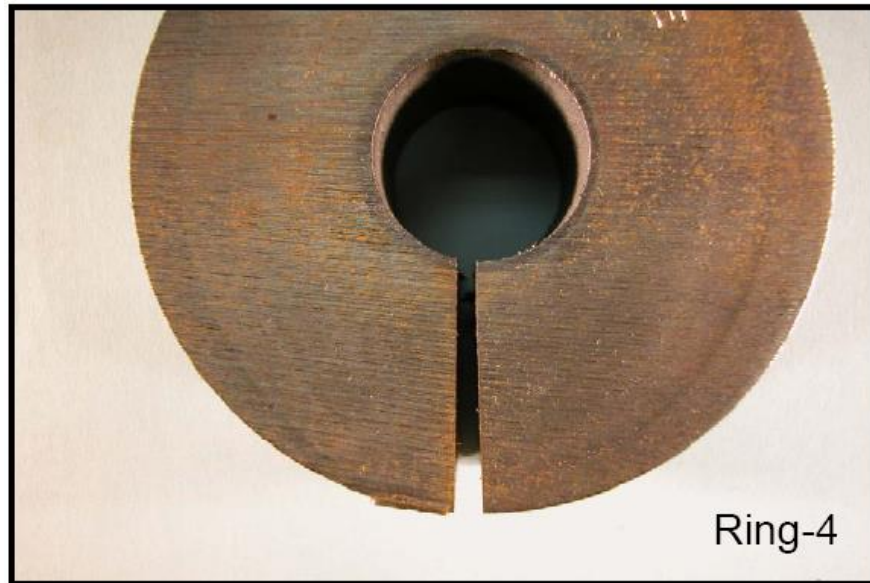


Fig. 3 Ring section taken from a gun tube lined with an Eagle Alloys liner. Residual stress in the tube has caused it to spring open.¹³

TPL suggested that the different histories of the gun tubes that were supplied to them caused the differences in the results. Government representatives disagreed. TPL presented a paper¹⁴ on their work at the 2005 Gun Tube Symposium but later withdrew it from publication, citing possible infringement of intellectual property rights. Relations with TPL deteriorated to the extent that in September 2005, the ARDEC legal office requested that all communication between government personnel and TPL cease. An attempt was made to terminate the contract with TPL, but this failed. TPL continued to work, eventually providing ARES with 4 full-length Ta2.5W-clad barrels.

Poor relations with TPL motivated ARL to seek another source of explosive bonding. Previous work at ARL with High Energy Metals, Inc. (HEMI; Sequim, WA) on bonding steel sheaths to W kinetic-energy penetrators suggested that this company might be successful. Three sets of steel barrel blanks and Stellite 25 liners were sent to HEMI, which was able to bond them on the first try.¹⁵ Push-out tests confirmed that the bond strength achieved was very high, even though the liner–gun tube interface was not always wavy.¹⁶

In the meantime, ARES was experiencing difficulty rifling the gun tubes that had been supplied by TPL. The tubes were first honed to obtain the proper inner bore

diameter and smooth surface. At this point, ARES noticed that in some instances the liner was not concentric with the outer surface of the tube. In another case, the tube was bent. These problems were eventually overcome, and ARES moved on to rifling the liner. This was done with a 2-point cutter, shown in Fig. 4. The cutter was placed in a holder called a quill, and this arrangement was pulled through the tube to form a pair of grooves. The process was repeated for each of the 9 pairs of grooves. Since only a small depth was obtained for each pass, a series of 24 cutting tools was used to make progressively deeper cuts. Even with this simple arrangement, ARES had difficulties in rifling the liner. In some cases, the cutter would get stuck; in others, the cutting tool would break. In some instances, the chips would lodge between the bushing used to center the quill in the tube.

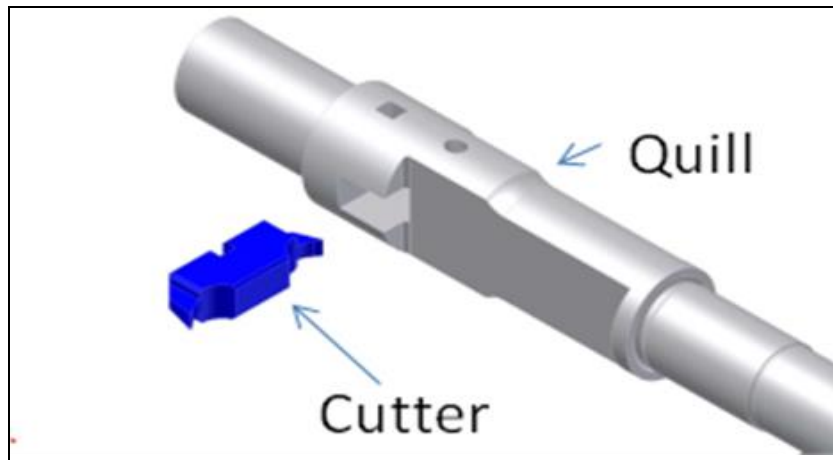


Fig. 4 Cutting tool showing the 2-point cutter and quill.¹³ The cutter fits in the slot in the quill.

To overcome ARES' inexperience with machining Ta10W, a representative from the National Center for Defense Manufacturing and Machining visited the ARES facility and suggested some changes in the cutter geometry. Eventually, the cutter geometry was redesigned.

In addition, very stringent tolerances on the tool dimensions had to be maintained, and ARES took on the task of grinding and inspecting the cutters. Even so, ARES continued to have problems machining the liners.

The Mantech program came to an end in the fall of 2005, although some barrel production was continued with unexpended funds. At the end of the program, the TRL had not changed a great deal. Little basic research had been done on the explosive bond, and the effect of the intermetallic layer was not understood. HEMI's success with Stellite 25 was promising but had not been demonstrated on a tube longer than 10 inches. The explosive bonding process had resulted in

residual stress in the gun barrel, but the effect of this stress on the machining operation was unknown. The problems encountered with rifling the liner indicated that the MRL was still quite low. In actual manufacturing, the 2-point cutter approach was too slow and would never be used. However, in the development phase of the effort it was sufficient to produce acceptable tubes.

4. Multiple Programs, 2005–2010

The Strategic Environmental Research and Development Program (SERDP) was established by the US Department of Defense (DoD) in 1990 to promote good environmental practices within DoD. The use of Cr electro-plating in gun tubes has long been recognized as hazardous to the environment because it involves hexavalent Cr, a known carcinogen. The explosive bonding technology offered a potential solution to this problem, and a SERDP in support of much-needed research in this area was established in 2005.

Based in part on the success that HEMI had with bonding a Stellite 25 liner to a gun tube section, Benét Laboratories began negotiations with them for additional bonding work. Procurement delays pushed the contract award well into 2006, but in February 2007 HEMI announced that it had clad two 10-inch barrel sections with Ta10W liners.

Meanwhile, TPL continued to supply ARES with full-length M242 barrels clad with Ta2.5W. These barrels were made by using M242 tubes with momentum traps at the thin (muzzle) end of the gun tube. Of the 4 barrels delivered, only 3 had acceptable bonds. ARES experienced more problems in trying to rifle the barrels, failing on the first 2 it tried. On the third attempt, a new set of cutters was ordered that further delayed machining for 5 months.

Work continued at HEMI, and in May of 2007 it delivered 4 more 12-inch tubes to Benét Laboratories lined with different refractory metals supplied by different vendors. Table 1 lists the details of the 4 tubes.

Table 1 Clad tube details

Tube Identification No.	Material	Vendor
1006	Ta10W	Eagle Alloys
1007	Ta5W2Mo	HC Starck
1008	Stellite 25	True Tube
1009	Ta10W	True Tube

Benét Laboratories measured the hot hardness of each of these liners, and the decision was made to go with Ta10W as the liner of choice based on this criterion. The fact that HEMI was able to bond this material to a steel tube was instrumental in this decision. Soon after, HEMI showed the ability to bond a Ta10W liner to a 3-ft barrel section.

The problems experienced by ARES in machining the lined gun tubes prompted further examination of the manufacturing process. There was some concern that the residual stress imparted by the explosive bonding process was adversely affecting the machining operation. It was suggested, although never proved, that when the liner was being rifled, enough material was removed to cause the gun tube to collapse on the cutters. In August 2007, ARL undertook a study of heat treating procedures that would allow a measure of stress reduction. This study was followed up with a similar study by Benét Laboratories. The outcome of these studies produced a recommendation that a thermal soak of the bonded tube be conducted at 525 °C. In the fall of 2007, Benét Laboratories also undertook a more thorough investigation of the machining parameters that went into the rifling of the bonded tube with a 2-point cutter. These parameters included the design of the cutter, the cutter material, the coating on the cutter, the quill design, and the lubricant to be used. A machining process was optimized and a patent was applied for (September 2011) that is still pending.

In December 2007, an Environmental Quality Technology (EQT) program was established at Benét Laboratories funded by the Army Research Development and Engineering Command as part of their Toxic Metal Reduction program. The purpose of this EQT program was to investigate the use of cold spray to produce Ta10W liners for explosive bonding. Cold spray is a process whereby metal particles are accelerated by introducing them into a high-velocity air stream. The particles impact a substrate and adhere to the substrate given the proper operating parameters. The benefit of cold spray over other spray processes is that the material properties of the particles are not heated significantly, thus their properties are not changed during the process. For a more thorough discussion, see Champagne.¹⁷

ARL had worked previously with Benét Laboratories to produce pure Ta cold-sprayed targets for the cylindrical magnetron sputtering program. ARL then took on the task of cold-spraying a 3-ft Ta10W tube for the EQT program. The metal powder could be made up of a mixture of Ta and W or it could be made of the actual alloy. Initial efforts established that the alloy was the better way to proceed. A 3-ft tube was eventually sprayed by ARL and sent to HEMI for explosive bonding, which awaits additional future funding. In the meantime, a reliable

source of Ta10W tubes (Plansee; Franklin, WA) was established, so interest in the cold-spray approach has diminished. The EQT program later transitioned into cold-spraying a thick coating on large-caliber gun tubes.

It took almost 6 months to conclude a contract with HEMI to produce full-length clad gun tube. At this point, HEMI decided not to use old M242 tubes as a starting point. Rather, it would start with D6AC steel barrel blanks that would eventually be machined into the final article. In the fall of 2008, one of the barrel blanks shattered during the explosive bonding process. An in-depth analysis by Benét Laboratories revealed that the billet used for this test was produced with the cold-drawn process. This gave the billet lower fracture toughness than billets made with the hot-forging process.¹⁸ Consequently, only hot-forged billets were used thereafter.

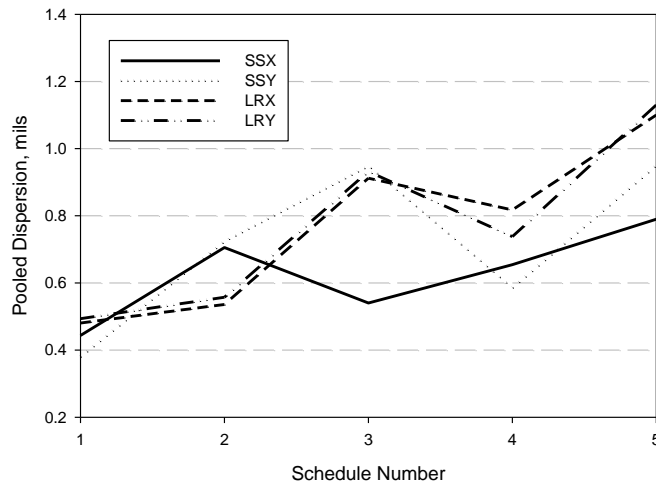
In November 2008, ARES began a SBIR program designed to firmly establish the machining parameters for the Ta10W liners. They developed a design of experiments matrix that varied the cutter material, cutter coating, tool angle, cutting fluid, and feed rate, and evaluated the results based on cutter wear, chip geometry, and quality of the groove. Four 12-inch barrels taken from the muzzle ends of M242 barrels were used for this study. A software program was used to find the optimum combination of tool parameters. A fifth 12-inch barrel was successfully produced with the optimum combination of tool parameters.¹⁹ This work established the parameters for the 2-point cutter, which laid the groundwork for the parameters used in the crown broach.

HEMI produced its first full-length clad barrel blank in December 2008 and soon produced 4 additional blanks clad with Ta10W. These 5 barrels were identified by serial numbers SN1–SN5. In machining the first barrel blank, ARES caused a short length of land to be removed near the muzzle of the gun. This defect argued against using SN1 in firing tests. The second tube that ARES machined had a groove mistakenly cut in the outer surface near the breech end of the gun. Finite element stress analyses indicated that the gun tube was safe to fire, but it too was placed in reserve. The inside diameter (ID) of the third tube to be machined was found to be too large; final machining was never done on this tube. ARES made another machining error on the fourth tube, removing too much material from each of the lugs that are used to hold the gun tube in the mount. The gun tube was sent to Benét Laboratories where a laser additive manufacturing technique was used to add the material back. The machining of the fifth tube was without incident. Appendix D lists all the M242 tubes made to date with comments about their disposition.

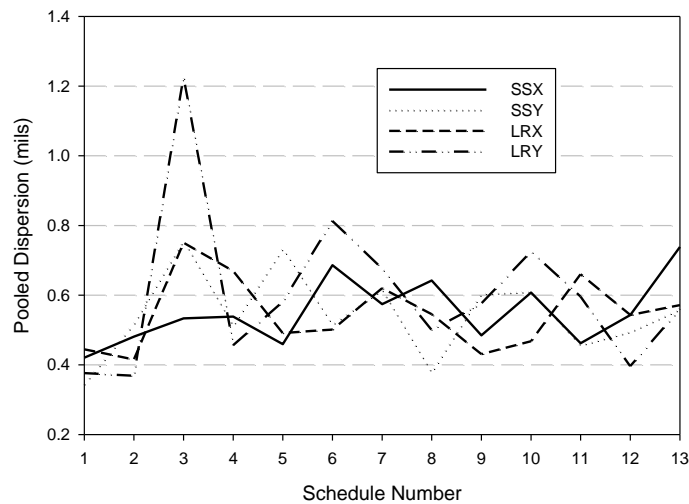
The number of defects that ARES produced in the final machining process can be attributed, in part, to its lack of experience in this area. They do not have a production line for finished M242 barrels. ARES normally produces Mann barrels with a constant outer diameter. Tapering and fluting the muzzle end of gun tubes were not normally done there. Appendix D lists several barrels that were oversize; that is, when the explosive bonding was done, it was found that the ID was too large for the liner to be rifled.

One result of explosive bonding a full-length barrel blank is that the ID is not always uniform. The first machining operation to be carried out is honing the gun tube to make the ID uniform. Normally very little material is removed honing, but if the variation in diameter is significant, the honing operation can consume a great deal of time.

It was decided to use barrel SN4 for the SERDP tests at Yuma Proving Ground (YPG), conducted during the spring and summer of 2010. The test plan called for SN4 and a standard Cr-coated M242 barrel to be fired side by side in a series of endurance and dispersion tests.²⁰ At shot number 3,650, the Cr-coated tube was pulled from service because it did not pass the Rock Island gage test. In addition, the Cr coating was observed to be severely damaged and the dispersion was on an upward trend (see Fig. 5a). Firing of the Ta10W-lined tube lasted for 11,205 shots, at which point it was retired from service because it did not pass the Rock Island gage test. However, there was little or no damage to the Ta10W liner, and the dispersion was not increasing, as shown in Fig. 5b. In any event, the lined barrel demonstrated in these specific tests the potential for an increase in service life by a factor of 3 greater than that of the coated tube.



5a. Dispersion in mils of the chromium-coated tube as a function of schedule number (shots fired). The key shows the individual results for single shot (SS) and low rate (LR) in the horizontal (X) and vertical (Y) directions.



5b. Dispersion in mils of the Ta10W-clad tube as a function of schedule number (shots fired). The key shows the individual results for single shot (SS) and low rate (LR) in the horizontal (X) and vertical (Y) directions.

Fig. 5 Dispersion measurements on Cr-coated and Ta10W-clad tubes²⁰

To help confirm these results, barrel SN5 was also put through the same endurance and dispersion tests as used for SN4. During the endurance tests, erratic flight behavior was observed visually via tracer rounds. Since no dispersion measurements were made during the endurance tests, this observation could not be quantitatively confirmed. Firing stopped with very little wear on the liner.

Before completion of the firing tests, Rowan Technology (Libertyville, IL) analyzed the costs associated with the new technology.¹³ They concluded that if the Ta10W-lined tube extended the service life of the M242 barrel by a factor of 2, then given certain assumptions about the number of barrels produced each year, introducing the technology would pay off in several years even though the initial costs were higher than those associated with Cr coating. This analysis was somewhat premature given that there were many unknowns at the time concerning the machining operations. In addition, the cost of the Ta10W liner was optimistically estimated to be \$2,000. The cost analysis for this technology was refined several times after the initial estimate but the general conclusion was the same.

The tests at YPG demonstrated that this technology was at or near a TRL of 7. The basic concept of explosive bonding was understood, and there were models that gave the interrelations between the bonding parameters. Two full-length barrels were clad with a Ta10W liner and successfully tested in a laboratory environment. These barrels were more than just prototypes; that is, they had the same configuration as a barrel that would actually be used in combat. There was no observable effect of the intermetallic layer on gun tube performance, so this issue did not merit any further investigation. The gun tube's performance exceeded that of the conventional Cr-coated tube.

The MRL was not so clear. Even though 2 full-length barrels had been successfully made and fired, 4 of the first 9 barrels had IDs that were oversize and not machineable. Heat-treating and machining studies had been conducted, and a reliable source of Ta10W tubes was established. However, the liners were still being rifled with a 2-point cutter. In practice, a multiple-head crown broach cutter would have to be used to reduce production time and costs. Finally, there were additional machining problems that surfaced later but were unknown at the time.

5. ESTCP, SBIR, and Mantech, 2011–2015

The Environmental Security Technology Certification Program (ESTCP) was established in 1995 to mature technologies that have been identified as solving DoD's environmental problems. Many of these technologies have proved feasible under SERDP. It was therefore natural to continue the efforts to demonstrate explosive bonding under ESTCP.

ESTCP required further validation of the SERDP firing results so a decision was made to repeat the original firing tests that used pure Ta with a more carefully controlled and thorough test plan using Ta10W liners. As with the original tests, the ammunition fired was the M919 with highly energetic propellant (also known

as 616W). The test plan also called for a standard production Cr-coated tube to be fired in comparison. The same series of endurance and dispersion tests as used in the SERDP tests would also be used.

The side-by-side comparison tests were conducted at YPG in late 2011 with barrel SN14.²¹ The Cr-coated tube was taken out of service at 740 shots when the ammunition began breaking up in the bore. The tube would probably have been condemned before that if an inspection had been made. The cause of the in-bore ammunition failure can be attributed to the removal of a large amount of coating and gun steel near the origin of rifling. Figure 6 shows a 3-dimensional (3-D) scan of the bore surface of the Cr-coated tube in this region.

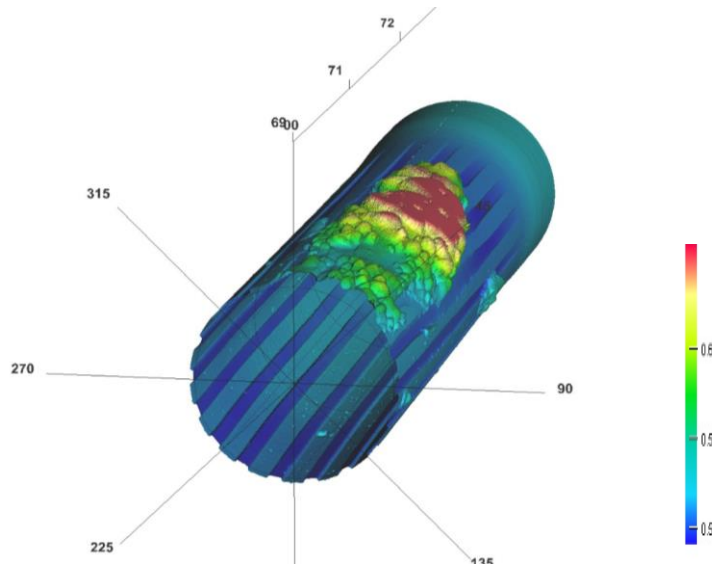


Fig. 6 Bore surface of the Cr-coated gun tube. The 3-D scan shows a gouge depth of 0.060 inch according to the scale to the right of the scan.

The tests of the Ta10W-lined tube were stopped at 900 shots, and the tube was taken out of service because it failed the Rock Island gage test. However, it was still firing with acceptable dispersion and little damage to the liner. There was one small pocket of removed liner near the origin of rifling that would probably have grown with further firing. The tests showed that the lined tube degraded much more gradually than the coated tube.

During the endurance tests of SN14, the same phenomenon that occurred with SN5 was observed. In the tests with SN14, however, the target miss distance was recorded. The measurements were not as accurate as those in an actual dispersion test because the impact points were outside the normal range of the Oehler acoustic measuring system. However, the measurements did indicate that there

was a problem with the tube. The horizontal miss distances are shown in Fig. 7. The plots show that as the number of shots in a given cycle increases, the miss distance generally increases.²²

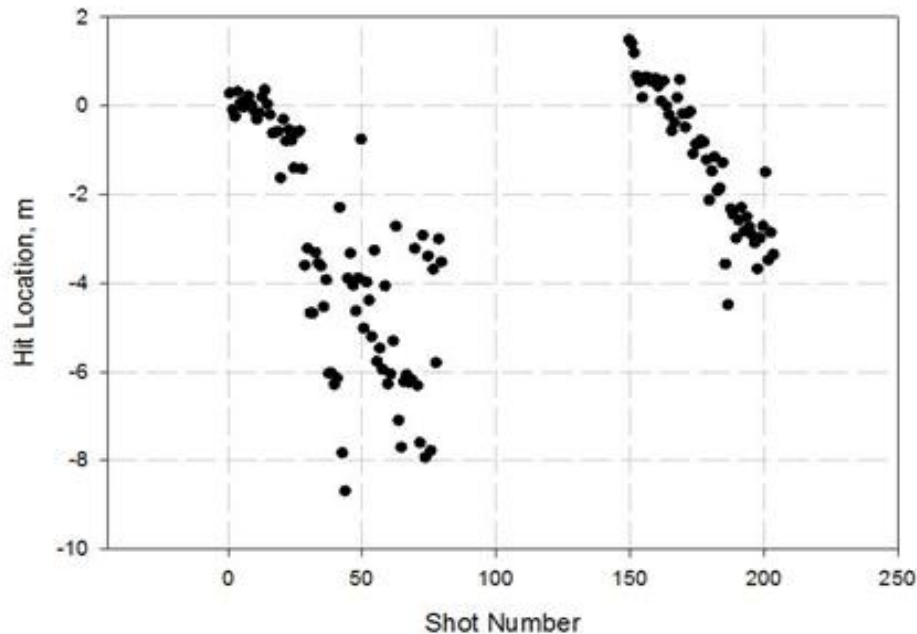


Fig. 7 Horizontal miss distances for barrel SN14 as a function of shot number. The barrel aimpoint moves to its original position between shot groups as a result of barrel cooling. A negative value of the hit location indicates that the aimpoint moved left.²²

A nondestructive test series was undertaken to determine the cause of the gun barrel movement. The most likely cause of the movement was assumed to be the effect of the high barrel temperature caused by the high-flame-temperature propellant. Barrel heating tests using SN14 conducted at ARL showed the effect of both a radial thermal gradient and an overall increase in the barrel temperature on the barrel movement. The thermal test results were consistent with the miss distance observations and confirmed that barrel heating contributed to the barrel motion.²²

Further insights into the cause of barrel motion were obtained from computed tomography (CT) scans of the barrel at selected points. Only the fluted portion of the gun tube was thin enough to be penetrated by X-rays. Figure 8 shows a scan through the fluted portion of SN14. Yellow circles have been added to the CT scan to help show that the liner is not concentric with the outer surface of the gun tube.

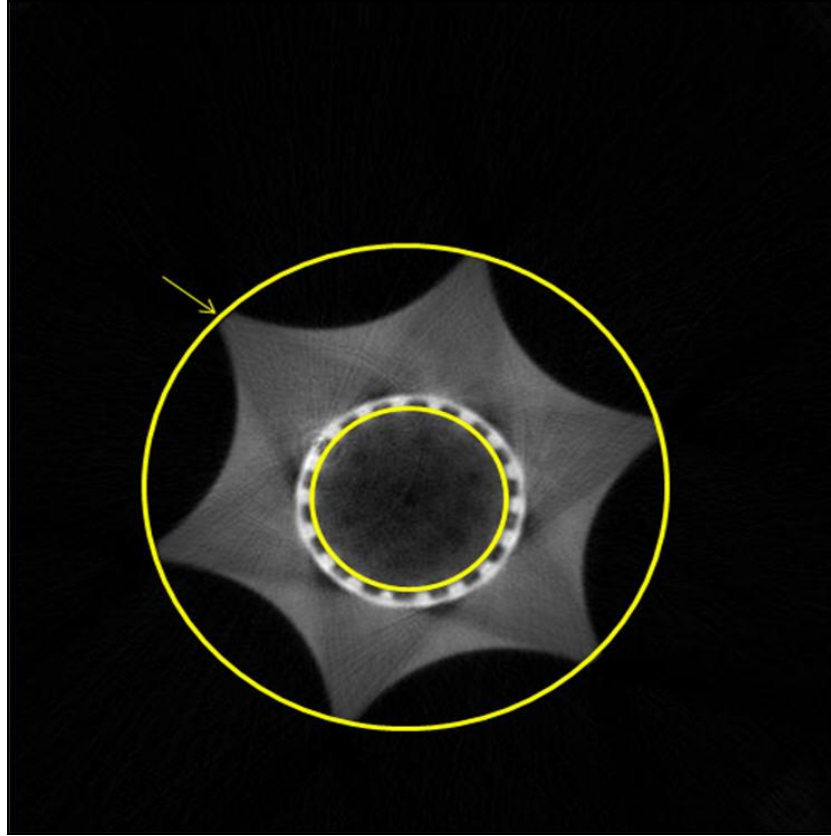


Fig. 8 CT scan of the fluted section of SN14. The yellow circles help show that the liner is not concentric with the outer contour of the gun tube.²²

As a result of these findings, the program was focused in 2 directions: 1) finding nondestructive techniques (NDTs) for inspection of the gun tubes and 2) machining procedures that would prevent the nonconcentricity of the liner. Attention turned to ultrasonics and eddy currents as possible NDTs.²³ Ultrasonics was found to be the most effective method of making gun-tube wall-thickness measurements, and several commercial hand-held instruments that used this approach were obtained. However, it was also found that these instruments were not useful in measuring wall thickness of lined gun tubes when the liner had been machined. Consequently, ARES changed its sequence of machining operations. The outer contour of the gun tube was machined first using ultrasonic measurements, and then the liner was rifled.

Even though the barrel blank is heat-treated to relieve the stresses induced by the explosive bonding process, there are still residual stresses. Consequently, when the barrel blank is tapered at the muzzle end, the barrel bends in response to stress relief caused by material removal. The barrel must then be restraightened. The

ultrasonic inspection of the tube assists in ensuring that the liner remains concentric to the outer contour of the tube. The new procedure was used with SN19, resulting in excellent concentricity.

The same success was not obtained with ARES' Phase 2 SBIR on machining technology. As a follow-up to their 2008 award, ARES began work on implementing crown broach cutters to rifle the lined tubes as would be done in a production environment. A crown broach set consists of 60 individual cutter heads, each containing 9 pairs of teeth. A single pass of the cutter head produces 18 grooves. Each pass increases the depth of the groove by approximately 0.0004 inch. Barrel SN11 was cut into 2 pieces, identified as SN11A and SN11B. On the 35th cutting pass on SN11A, a tooth broke on the crown broach. The same thing happened when SN11B was rifled.

Benét Laboratories conducted a root cause analysis. The material used in the teeth was found to be within the specified material properties. The 2 tubes were sectioned and the liner/outer-contour concentricity of each tube was found to be good. Inspection of the dimensions and shape of the crown broaches indicated several problems, none of which was the sole cause of the tooth breakage. The dimensions of several key features were found to be out of specification, so the angle of the cutting tooth could not be checked. The clearance specified between the quill bushing and bore tube was much larger than the amount of depth cut. This would allow the quill to move off axis, causing uneven cutting. Inspection of SN11B showed that galling had led to a build-up of Ta10W on the tooth that broke. Possible causes of the galling were 1) dull or chipped tooth, 2) inadequate cooling at the tooth location, 3) chip interference with the cutting process, 4) broach moving off axis, and 5) radial misalignment of the broach. An extensive program was recommended to investigate all of these possibilities, but no action has been taken as of the date of this report, primarily due to lack of funds.

To further the validation of the explosive bonding technology, additional firing tests were planned to be conducted at YPG. Several clad M242 tubes (SN13, SN15, SN17, and SN18) were available for these tests. However, all these tubes had been made with the old machining process that resulted in nonconcentricity of the liner and outer contour of the gun tube. CT scans were made of the tubes to determine the amount of nonconcentricity in each, and it was found that SN15 was the best of the 4. The test plan called for a repeat of the tests involving SN4, except that there was no Cr-coated M242s tested. In addition, the criterion for stopping the tests was reconsidered. It was not known ahead of the test what the initial dispersion would be. Consequently, it was decided to stop the tests after the dispersion exceeded 3 times the initial dispersion rather than setting a specific value of dispersion.

All 4 gun tubes were sent to YPG, and dispersion tests were conducted on each. It was found that SN15 had the lowest dispersion, so this was the tube selected for the firing tests. The tube had over 14,000 rounds fired when the testing was stopped at cycle 38. During this cycle, some low velocities were recorded during the dispersion tests, and impact strike points were far from the target. No dispersion was measured for this cycle because the data cable was shot out before all the data were collected. The gun tube was still in good firing condition and passed the Rock Island gage test.

It was also realized at this point that the criterion to stop the tests was ambiguous due to the large degree of scatter in the dispersion data. The initial dispersion, taken from the screening tests for SN15, was 0.39×0.38 -mil horizontal and vertical dispersion, respectively. Applying the criterion, the tests should stop when the dispersion reaches 1.17×1.14 mil. Figure 9 shows the horizontal dispersion for SN15. For the most part, it is below 1 mil. There was one excursion to 1.14 mil at shot number 12,868. However, for the next dispersion determination, the horizontal dispersion dropped below 1 mil. Stopping the tests after one large excursion does not make sense because the dispersion drops back below the threshold on the next cycle.

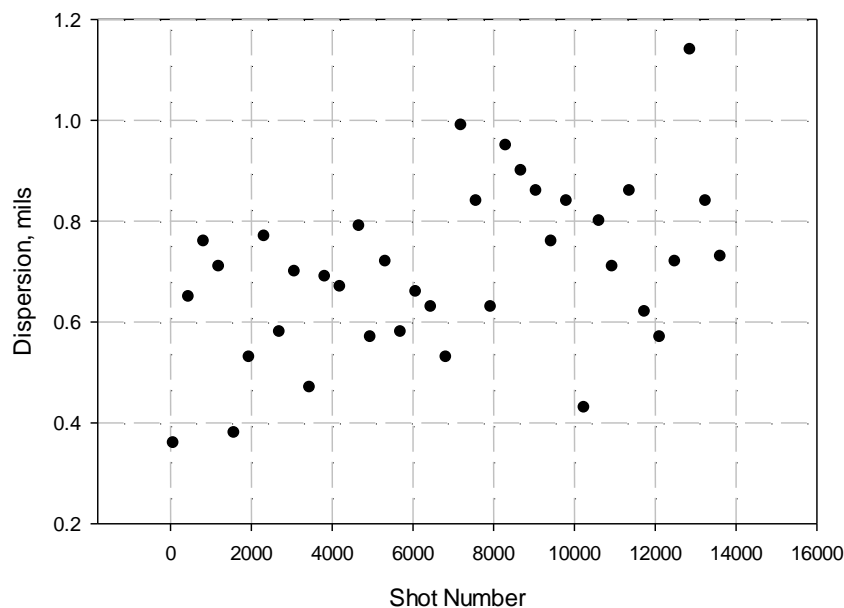


Fig. 9 Horizontal dispersion for SN15

At this point, a case can be made for assigning a TRL of 8 to the explosive bonding of a Ta10W liner to an M242 gun tube. It was demonstrated that the lined gun tube was capable of being fired under conditions that were far more stressful than actual combat conditions. The most recent test series demonstrated a service-

life extension of a factor of 4 compared with that of a standard Cr-coated gun tube. The actual service life of the Ta10W-lined gun tube has not been determined because the endurance tests were halted prematurely.

A US Marine Corps representative stationed at Camp Pendleton, CA, requested a Ta10W-lined tube for training exercises. The idea was to provide the Army with test data on the wear of the tube in simulated combat conditions. To transfer a gun tube to the Marines, a safety release was required. ARL's efforts to obtain a safety release were not successful. The Army Test and Evaluation Command (ATEC) did not concur for numerous reasons (Masino TR, ATEC, email dated 2014 Sep 24). If the safety release had been approved, the case could be made for a TRL of 9. In fact, a great deal more testing would be required for a safety release to be granted.

The MRL of the explosive bonding technology is at a much lower level. The typical approach to rifle the Ta10W liner in a production environment would be to use crown broach cutters. There are still unsolved (but solvable) problems associated with those cutters. It may be that waterjet cutting will be the best approach to rifling the tube due to cost considerations. This technology can be rated at an MRL of 3. If the demonstration of rifling an actual Ta10W-lined tube occurs, the MRL could be considered as high as 4 for this technology. The next step would be to place a waterjet machine in an actual production environment.

Cost is still an important consideration when adopting explosive bonding technology. The cost of a standard M242 gun tube is approximately \$7,200 (Polzin E, Camp Pendleton, CA, email dated 2014 Dec 9). Therefore, assuming a life extension by a factor of 4, the Ta10W-lined tube must be made for less than \$28,800 for it to be economically viable.

6. Future Efforts

The lack of success in trying to use a crown broach to rifle the Ta10W liner led to attempts to find other technologies to do this job. In 2013, Ormond LLC (Auburn, WA), which had experience cutting grooves in both metallic and ceramic materials, was awarded a Phase 1 SBIR to investigate the use of waterjet cutting to rifle the liner. Waterjet uses a stream of abrasive particles entrained in water to cut through many types of materials. The primary question was whether the nozzle for streaming the abrasive water mixture could be made small enough to fit inside the liner. Ormond solved this problem and was awarded a Phase 2 SBIR with the goal of producing a machine (minus the necessary pumps) that could rifle an M242 cannon. In the fall of 2014, Ormond demonstrated a machine that was capable of rifling a stainless steel tube that was 84 inches long and had an ID of

25 mm. Since the cutting parameters for stainless steel and Ta10W are not very different, it was expected that rifling an M242, to be completed by the end of fiscal year 2015, would be successful. The only open question was whether the dimensional tolerances on the grooves could be met.

Using a waterjet in the honing process is also being considered. If successful, this would save considerable time and expense. The current approach uses a honing stone to remove small amounts of material, make the bore diameter uniform along the tube axis, and provide a smooth surface. However, this process is very slow. Waterjet is expected to quickly make the bore diameter uniform, with only 1 or 2 passes of the honing stone needed to make a smooth surface.

General Dynamics (GD, Falls Church, VA) has been awarded a contract to manufacture Ta10W-lined M242 gun tubes, starting with lined barrel blanks furnished by HEMI. If GD is successful, one might consider the MRL level to be 7 because the manufacture of the tube will have been demonstrated in a production environment. At that point, consideration can be given to a Milestone B decision to go on to engineering and manufacturing development.

The use of explosive bonding will also be attempted at smaller calibers. In particular, a Technology Transition Agreement has been signed by the Army project manager for PEO Soldier Weapons for a Ta10W-lined M2 0.50-cal. machine gun barrel. HEMI has been able to explosively bond a liner to an M2 barrel blank, and the lessons learned from rifling the M242 can be applied to machining the barrel blank to make the finished product. A micrograph of the Ta liner attached to the steel blank is shown in Fig. 10.

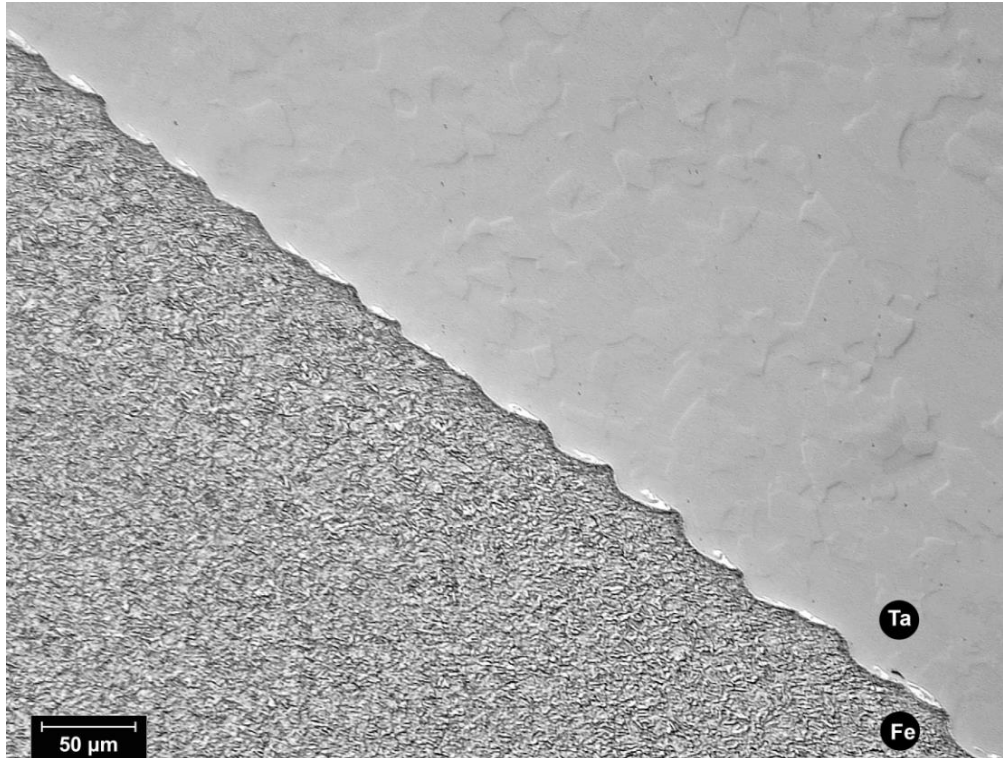


Fig. 10 Interface between Ta10W liner and steel barrel blank. The wavy pattern indicates a good bond. (Courtesy of High Energy Metals, Inc.)

7. Conclusions

This report presents the research and development (R&D) efforts that have gone into explosively bonding a Ta10W liner into an M242 25-mm medium-caliber gun tube. The EBP started in the late 1990s and has lasted more than 15 years. It has been funded under numerous programs, including SBIR, ESTCP, Mantech, and SERDP. The following conclusions directly related to this program can be made:

- Basic research is relatively inexpensive; however, costs go up as the TRL and MRL increase. In particular for the EBP, acceptance, validation, and safety testing can be extremely expensive. Good progress at each TRL and MRL must be obtained for the program to justify further funding.
- In most R&D programs, unanticipated problems will arise. The EBP was no exception. The 2 prominent unanticipated problems for this program were the type of starting material needed for the barrel blank and the nonconcentricity of the liner and outer contour of the gun tube. Additional programs were needed to determine the cause of the problems and potential solutions.

- The EBP started as an SBIR program. The main rationale of the SBIR program is to have small businesses get a product to market as soon as possible. Sometimes the rush to commercialize a good idea is accompanied by a lack of basic research or understanding of the processes involved. This appears to be the case with TPL, Inc., which did not have sufficient background in explosive bonding to weld anything other than pure Ta and Ta2.5W.
- One can question the appropriateness of the SBIR process to produce an item that does not have a commercial application. If the only customer is the US Army, adding it to the Army inventory will require additional tests, reviews, approvals, cost analyses, etc. that the small business cannot or will not fund. In some instances, like the current one, certain problems need to be solved even before the item is shown to be acceptable. Again, the small business is not the entity that will fund this work.
- The EBP can be characterized as coming from a technology push rather than a customer pull. Army research organizations realized the need to extend the service life of gun tubes as well as offering the potential for use of more lethal ammunition. In addition, elimination of chrome coating is a desirable outcome. However, the program manager has not signed a Technology Transition Agreement to support the development of this technology.
- The success of waterjet cutting is critical to reducing machining costs and making the explosive bonding of Ta10W liners economically feasible. Unless more effort is put into solving problems with crown broach cutting, waterjet cutting may be the only machining technology available.
- Technology transfer is an important part of the R&D process. For the EBP program, technology was developed by private companies outside Army organizations; that is, explosive bonding technology was developed by HEMI and the company is willing to license the technology. Waterjet cutting was developed by Ormond, which will also license its technology.
- For adoption into Army systems, a high TRL is necessary. However, it is not sufficient. The high TRL must be accompanied by a high MRL. For the EBP, the TRL is high but the MRL is not. It is expected that current efforts will raise the MRL to a point where it can be considered for a Milestone 1 decision.

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Appendix A. Explosive Bonding Description

Explosive bonding has been used commercially for over 40 years to weld dissimilar metals that are otherwise difficult to join. The technology is relatively mature, and the governing equations have been documented in other journals. Carpenter and Wittman¹ provide an excellent review of the technology, and most of what is presented here is taken from their work. Even though their equations apply to flat-plate collisions, they are taken over here for tubular geometry.

The process used to bond a liner to a gun tube can be accomplished in a number of ways. In one possible way, the liner is first inserted into the gun tube and centered with appropriate spacers to achieve the desired standoff. The arrangement might be vertical or horizontal. The liner extends a short distance out of both ends of the gun tube. Next the liner is filled with a low-detonation-velocity explosive, which is then detonated, forming the bond between the liner and gun tube.

Figure A-1 shows a schematic cross section of the liner–gun tube arrangement and the important explosive bonding parameters. A constant standoff geometry is used for bonding the liner, also known as the donor tube. In this figure, V is the donor tube radial velocity, D is the detonation velocity of the explosive, V_c is the collision point velocity, and α is the angle between the donor tube and the gun barrel at the point of collision.

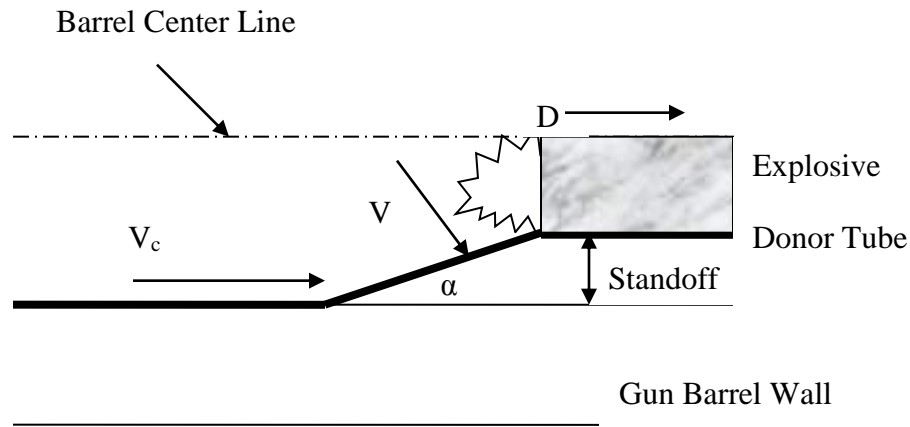


Fig. A-1 Geometry of the explosive bonding setup

In general,

$$V_c = D, \quad (1)$$

and

¹ Carpenter SH, Wittman RH. Explosion welding. *Ann Rev Mat Sci.* 1975;5:177–199.

$$V = 2D \sin\alpha/2. \quad (2)$$

For small values of α ,

$$V = D \sin\alpha. \quad (3)$$

The first consideration is the minimum impact pressure needed to make the explosive bonding process work. Carpenter and Wittman¹ provide an empirically successful relation between the minimum donor tube impact velocity V_{\min} and the ultimate tensile strength σ_{ts} as follows:

$$V_{\min} = (\sigma_{ts} / \rho)^{1/2}, \quad (4)$$

where ρ is the donor tube density. It is presumed that the ultimate tensile strength is that strength measured at room temperature. However, it is expected that the donor tube will be heated during plastic deformation, lowering its strength. Consequently, the V_{\min} calculated may overestimate the actual value of V_{\min} . In addition, these same authors acknowledge that it would be better to use the Hugoniot elastic limit (HEL) to calculate V_{\min} (in another formula). However, the value of HEL for many alloys is not always available. Consequently, for sake of comparison among the alloys examined in this report, the ultimate tensile strength will be used in the calculations.

The second consideration is the existence of a transition collision velocity. Below this velocity, researchers have found the bond line to be flat, and above the collision velocity, they found the bond to be wavy. A wavy bond line is indicative of a good bond, implying that there is a lower limit to the collision velocity for a good bond. This transition velocity will be designated as V_T . Cowan et al.² relate V_T to the density of the donor tube, ρ to the density of the gun barrel ρ_b , and H_F and H_B to the diamond pyramid hardness of the donor tube and gun barrel, respectively, given a consistent set of units, in the following way:

$$V_T = \sqrt{2R_T(H_F + H_B)/(\rho + \rho_b)}. \quad (5)$$

R_T is an empirically determined parameter that, for a wide range of metals, averages to 10.6 (no units).

Wittman³ derived a formula for the maximum donor tube velocity that would not result in melt-induced defects destroying the bond strength. This maximum velocity, V_{\max} , can be calculated from the following equation:

² Cowan GR, Bergman OR, Holtzman AH. Mechanism of bond zone wave formation in explosion-clad metals. Met Trans B. 1971;2(11):3145–3155.

³ Wittman RH. Proceedings of the Second International Symposium on the Use of Explosive Energy Manufacturing Metallic Materials. Marianske-Lazne, Czechoslovakia; 1973.

$$V_{\max} = \frac{(T_{\text{MP}} C_B)^{1/2} (KCC_B)^{1/4}}{N V_c (\rho h)^{1/4}}. \quad (6)$$

The material characteristics associated with the flyer plate are as follows: 1) T_{MP} , the melting point in degrees Centigrade; 2) C_B , the bulk sound speed; 3) K , the thermal conductivity; 4) C , the specific heat; 5) h , the flyer plate thickness; and 6) ρ , the flyer plate density.

N is a constant that is not explicitly provided in Carpenter and Wittman.¹ However, it can be derived from the table of material properties provided in this reference. First, calculate the value of V_{\min} using the values of ρ and σ_{ts} with Eq. 4. Next, determine NV_{\max} from the other parameters provided in Carpenter and Wittman and Eq. 6. The value of N can then be determined from the ratio of V_{\max} to V_{\min} provided in Carpenter and Wittman. For the 12 metals listed, the average value of N is 0.11, with a mean deviation of 0.009.

There is experimental evidence that a jet is formed at the intersection of colliding surfaces during the explosive bonding process.⁴ It is generally accepted that this jet rids the colliding surfaces of any oxides and promotes a metallurgical bond. However, not all collisions result in a jet. Walsh et al.⁵ first proposed the concept of a critical collision angle for jet formation. This is the minimum angle at a specified collision velocity that is required for jet formation. Cowan et al.² extended this work to asymmetric collisions and give the angle α in terms of the shock parameters and V_c , as follows:

$$\tan \alpha = U_p(V_c^2 - U_s^2)^{1/2} / (V_c^2 - U_p U_s). \quad (7)$$

At the critical collision angle, the partial derivative of the pressure with respect to α is zero (fixed V_c).⁴ The pressure P is related to the shock velocity U_s and the particle velocity U_p through the following usual equation:

$$P = \rho U_s U_p. \quad (8)$$

The empirically determined relation between U_s and U_p is also required to determine the critical angle. The relation between the shock velocity and V_c is given by the following:

$$U_s = V_c \sin \beta, \quad (9)$$

⁴ Bergmann OR, Cowan GR, Holtzman AH. Experimental evidence of jet formation during explosion cladding. Transactions of the Metallurgical Society of AIME. 1966;236:646.

⁵ Walsh JM, Schreffler RG, Willig FJ. Limiting conditions for jet formation in high velocity collisions. Journal of Applied Physics. 1953;24(3):349–359.

where β is the angle between the shock front and the material flow vector into the collision point viewed from a frame of reference that is stationary with respect to the collision point.

These equations can be used to generate plots that give the allowable material parameters that will produce an acceptable bond for a given range of detonation velocities. An example calculation is shown in de Rosset.⁶

⁶ de Rosset WS. Explosive bonding of refractory metal liners. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2004 Aug. Report No.: ARL-TR-3267. Also available at: <http://www.arl.army.mil/arlreports/2004/ARL-TR-3267.pdf>.

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Appendix B. Technology Readiness Level (TRL) Definitions

Technology Readiness Level	Description	Supporting Information
1. Basic principals observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.	Published research that identifies the principles that underlie this technology. References to who, where, and when.
2. Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that outline the application being considered and provide analysis to support the concept.
3. Analytical and experimental critical function and/or characteristics proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.
4. Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively low fidelity compared with the eventual system. Examples include ad hoc hardware in the laboratory.	System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
5. Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonable realistic supporting elements so it can be tested in a simulated environment. Examples include high-fidelity laboratory integration of components.	Results from testing a laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the relevant environment differ from the expected operational environment? How do the test results compare with expected results? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?

Definitions, continued

Technology Readiness Level	Description	Supporting Information
6. System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
7. System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an actual operating environment such as an aircraft, vehicle, or space.	Results from testing a prototype system in an operational environment. Who performed the tests? How did the tests compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
8. Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
9. Actual system proven through successful mission operations.	Application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.	Operational test and evaluation reports.

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Appendix C. Manufacturing Readiness Level (MRL) Definitions

There are 10 Manufacturing Readiness Levels (MRLs) (numbered 1–10) that are correlated to the 9 Technology Readiness Levels (TRLs) in use. The final level (MRL 10) measures aspects of lean practices and continuous improvement for systems in production.

C.1 MRL 1: Basic Manufacturing Implications Identified

This is the lowest level of manufacturing readiness. The focus is to address manufacturing shortfalls and opportunities needed to achieve program objectives. Basic research (i.e., funded by budget activity) begins in the form of studies.

C.2 MRL 2: Manufacturing Concepts Identified

This level is characterized by describing the application of new manufacturing concepts. Applied research (i.e., funded by budget activity 6.2) translates basic research into solutions for broadly defined military needs. Typically, this level of readiness in the science and technology (S&T) environment includes identification, paper studies and analysis of material and process approaches. An understanding of manufacturing feasibility and risk is emerging.

C.3 MRL 3: Manufacturing Proof of Concept Developed

This level begins the validation of the manufacturing concepts through analytical or laboratory experiments. This level of readiness is typical of technologies in the S&T funding categories of Applied Research and Advanced Development (i.e., funded by budget activity 6.3). Materials and/or processes have been characterized for manufacturability and availability, but further evaluation and demonstration is required. Experimental hardware models have been developed in a laboratory environment that may possess limited functionality.

C.4 MRL 4: Capability to Produce the Technology in a Laboratory Environment

This level of readiness is typical for S&T programs in the budget activity 6.2 and 6.3 categories and acts as an exit criterion for the Materiel Solution Analysis Phase approaching a Milestone A decision. Technologies should have matured to at least TRL 4. This level indicates that the technologies are ready for the Technology Development Phase of acquisition. At this point, required investments, such as manufacturing technology development, have been identified. Processes to ensure manufacturability, producibility, and quality are in place and are sufficient to produce technology demonstrators. Manufacturing risks have been identified for building prototypes, and mitigation plans are in place. Target cost objectives have been established, and manufacturing cost drivers have

been identified. Producibility assessments of design concepts have been completed. Key design performance parameters have been identified as well as any special tooling, facilities, material handling and skills required.

C.5 MRL 5: Capability to Produce Prototype Components in a Production-Relevant Environment

This level of maturity is typical of the midpoint in the Technology Development Phase of acquisition or, in the case of key technologies, near the midpoint of an Advanced Technology Demonstration project. Technologies should have matured to at least TRL 5. The industrial base has been assessed to identify potential manufacturing sources. A manufacturing strategy has been refined and integrated with the risk management plan. Identification of enabling/critical technologies and components is complete. Prototype materials, tooling and test equipment, as well as personnel skills have been demonstrated on components in a production-relevant environment, but many manufacturing processes and procedures are still in development. Manufacturing technology development efforts have been initiated or are ongoing. Producibility assessments of key technologies and components are ongoing. A cost model has been constructed to assess projected manufacturing cost.

C.6 MRL 6: Capability to Produce a Prototype System or Subsystem in a Production-Relevant Environment

This MRL is associated with readiness for a Milestone B decision to initiate an acquisition program by entering into the Engineering and Manufacturing Development (EMD) Phase of acquisition. Technologies should have matured to at least TRL 6. It is normally seen as the level of manufacturing readiness that denotes completion of S&T development and acceptance into a preliminary system design. An initial manufacturing approach has been developed. The majority of manufacturing processes have been defined and characterized, but there are still significant engineering and/or design changes in the system itself. However, preliminary design of critical components has been completed and producibility assessments of key technologies are complete. Prototype materials, tooling and test equipment, as well as personnel skills have been demonstrated on systems and/or subsystems in a production-relevant environment. A cost analysis has been performed to assess projected manufacturing cost versus target cost objectives, and the program has in place appropriate risk reduction to achieve cost requirements or establish a new baseline. This analysis should include design trades. Producibility considerations have shaped system development plans. The Industrial Capabilities Assessment (ICA) for Milestone B has been completed. Long-lead and key supply chain elements have been identified.

C.7 MRL 7: Capability to Produce Systems, Subsystems, or Components in a Production-Representative Environment

This level of manufacturing readiness is typical for the midpoint of the EMD Phase leading to the Post-CDR Assessment. Technologies should be on a path to achieve TRL 7. System detailed design activity is underway. Material specifications have been approved, and materials are available to meet the planned pilot-line build schedule. Manufacturing processes and procedures have been demonstrated in a production-representative environment. Detailed producibility trade studies and risk assessments are underway. The cost model has been updated with detailed designs, rolled up to system level, and tracked against allocated targets. Unit cost reduction efforts have been prioritized and are underway. The supply chain and supplier quality assurance have been assessed and long-lead procurement plans are in place. Production tooling and test equipment design and development have been initiated

C.8 MRL 8: Pilot-Line Capability Demonstrated; Ready to Begin Low-Rate Initial Production (LRIP)

This level is associated with readiness for a Milestone C decision and entry into LRIP. Technologies should have matured to at least TRL 7. Detailed system design is essentially complete and sufficiently stable to enter low-rate production. All materials are available to meet the planned low-rate production schedule. Manufacturing and quality processes and procedures have been proven in a pilot line environment and are under control and ready for low rate production. Known producibility risks pose no significant challenges for low rate production. The engineering cost model is driven by detailed design and has been validated with actual data. The ICA for Milestone C has been completed and shows that the supply chain is established and stable.

C.9 MRL 9: Low-Rate Production Demonstrated; Capability in Place to Begin Full-Rate Production (FRP)

At this level, the system, component, or item has been previously produced, is in production or has successfully achieved LRIP. Technologies should have matured to TRL 9. This level of readiness is normally associated with readiness for entry into FRP. All systems engineering/design requirements should have been met such that there are minimal system changes. Major system design features are stable and have been proven in test and evaluation. Materials are available to meet planned rate production schedules. Manufacturing process capability in a low-rate production environment is at an appropriate quality level to meet design key characteristic tolerances. Production risk monitoring is ongoing. LRIP cost targets

have been met, and learning curves have been analyzed with actual data. The cost model has been developed for FRP environment and reflects the impact of continuous improvement.

C.10 MRL 10: FRP Demonstrated and Lean Production Practices in Place

This is the highest level of production readiness. Technologies should have matured to TRL 9. This level of manufacturing is normally associated with the production or sustainment phases of the acquisition life cycle. Engineering/design changes are few and generally limited to quality and cost improvements. System, components, or items are in FRP and meet all engineering, performance, quality and reliability requirements. Manufacturing process capability is at the appropriate quality level. All materials, tooling, inspection and test equipment, facilities, and manpower are in place and have met FRP requirements. Rate production unit costs meet goals, and funding is sufficient for production at required rates. Lean practices are well established, and continuous process improvements are ongoing. Although the MRLs are numbered, the numbers themselves are unimportant. The numbers represent a nonlinear ordinal scale that identifies what maturity should be as a function of where a program is in the acquisition life cycle. Using numbers is simply a convenient naming convention.

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Appendix D. Barrel Listing and Disposition

Barrel Designation	Liner Vendor	Final Machining Date	Comments
SN1	Grandview	6/03/09	Chip was removed from rifling about 4 inches from the muzzle; sent to Yuma Proving Ground (YPG) as backup.
SN2	Grandview	8/19/09	ARES, Inc., accidentally cut a groove around the outer surface of the tube; unlikely to be fired.
SN3	Wah Chang	N/A	Tube inner diameter (ID) was oversized; no machining was done. Bore not concentric with the outer diameter (OD). Cut into pieces for studies.
SN4	Plansee	4/10/10	ARES machined lugs incorrectly; Benét Laboratories replaced material with laser-engineered net shaping process; test fired 11,205 rounds at YPG from 5/10/10 to 9/30/10.
SN5	Wah Chang	4/20/10	Test fired 1,500 rounds at YPG; high dispersion noted during endurance tests; found that liner was not concentric with the barrel OD.
SN6	Plansee	N/A	Tube ID was oversized; cut up for studies. One section sent to ATK for electro-chemical machining study. Others used for honing studies at ARES.
SN7	Plansee	N/A	Tube ID was oversized. Used by ARES for cutter durability study; no final machining.
SN8	Plansee	N/A	Cutter stuck and broke, making a small chip in the lands near the muzzle; no final machining.
SN9	Skipped this number.
SN10	Plansee	N/A	Small Business Innovation Research (SBIR) barrel; oversized ID on one end.
SN11	Plansee	N/A	Cut into 2 pieces; crown broach studies at ARES; not final machined.
SN12	Plansee	...	Unfinished SBIR barrel located at ARES.
SN13	Plansee	...	SBIR barrel; sent to YPG as back-up barrel.
SN14	Plansee	8/15/11	ARES SBIR barrel; shipped to YPG 9/11/11 for tests with 616W.
SN15	Plansee	????	Fired over 14,000 rounds at YPG Environmental Security Technology Certification Program tests.
SN16	Plansee	N/A	Environmental Quality Technology barrel; cut into pieces for honing study.
SN17	Plansee	...	Sent to YPG as back-up barrel.
SN18	Plansee	...	Sent to YPG as back-up barrel.
SN19	Plansee	N/A	New processes ensured that liner was concentric with OD; not rifled or machined as yet.
SN20	N/A	...	Lined with copper; machining OD study for ARES.
SN21	Plansee	...	Cut up and used for bore removal study at ARES.
SN22	Plansee	...	Cut up and used for bore removal study at ARES.
SN23	Plansee	...	Finished barrel sent to High Energy Metals, Inc., for use in co-forge process at Plansee.
SN24	Plansee	...	Cut up and used for bore removal study at ARES.
SN25	N/A	...	Lined with copper; machining OD study for ARES.

List of Symbols, Abbreviations, and Acronyms

3-D	3-dimensional
α	collision angle between donor tube and gun tube
ARDEC	US Army Armament Research, Development and Engineering Center
ARL	US Army Research Laboratory
ATEC	US Army Test and Evaluation Command
C	specific heat
C_B	bulk sound speed
Cr	chromium
CT	computed tomography
DoD	Department of Defense
DM	electro-discharge machining
EBP	Explosive Bonding Program
EQT	environmental quality technology
ESTCP	Environmental Security Technology Certification Program
FRP	full-rate production
GD	General Dynamics
h	donor tube wall thickness
HEL	Hugoniot elastic limit
HEMI	High Energy Metals, Inc.
H_f	diamond pyramid hardness of donor tube
H_b	diamond pyramid hardness of gun tube
ICA	Industrial Capabilities Assessment
ID	inside diameter
K	thermal conductivity
LRIP	low rate initial production
Mantech	Manufacturing Technology

Mo	molybdenum
MRL	Manufacturing Readiness Level
M242	25-mm medium-caliber cannon designation
N	empirical parameter used in V_{max} equation
NDT	nondestructive technique
OD	outer diameter
ρ	material density
ρ_b	density of gun tube
R&D	research and development ⁶
R_T	empirically determined parameter used to calculate V_T
S&T	science and technology
SBIR	Small Business Innovative Research
SERDP	Strategic Environmental Research and Development Program
SN _n	lined tube identification, $1 \leq n \leq 25$
σ_{ts}	tensile strength
Ta	tantalum
Ta4Mo	Ta alloy made with 4% Mo
Ta2.5W	Ta alloy made with 2.5% W
Ta5W2Mo	Ta alloy made with 5% W and 2% Mo
Ta10W	Ta alloy made with 10% W
T_{MP}	melting point
V	collision velocity
V_d	detonation velocity
V_{max}	maximum collision velocity
V_{min}	minimum collision velocity
V_T	transition velocity
W	tungsten
YPG	Yuma Proving Ground

1 DEFENSE TECHNICAL
(PDF) INFORMATION CTR
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2 DIRECTOR
(PDF) US ARMY RESEARCH LAB
RDRL CIO LL
IMAL HRA MAIL & RECORDS
MGMT

1 GOVT PRINTG OFC
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